MODELING RERTR EXPERIMENTAL FUEL PLATES USING THE PLATE CODE

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ABSTRACT

Modeling results using the PLATE dispersion fuel performance code are presented for the U-Mo/Al experimental fuel plates from the RERTR-1, -2, -3 and -5 irradiation tests. Agreement of the calculations with experimental data obtained in postirradiation examinations of these fuels, where available, is shown to be good. Use of the code to perform a series of parametric evaluations highlights the sensitivity of U-Mo dispersion fuel performance to fabrication variables, especially fuel particle shape and size distributions.

1. Introduction

The PLATE (Plate Lifetime Accurate Thermal Evaluation) dispersion fuel performance code has been under development for several years. Motivation for its development came as a result of the need to evaluate the thermal conditions of experimental U-Mo/Al fuel plates during their irradiation lifetime. However, it had been observed in postirradiation examinations (PIE) that U-Mo/Al dispersion fuels can produce significant quantities of a low-conductivity reaction product phase during irradiation, with much of the high-conductivity Al matrix phase consumed in the process [1]; for this reason it was recognized that any reasonable thermal evaluation leading to accurate fuel plate temperatures would have to include this phenomenon in a time-dependent way. PLATE has provided the capability to perform the needed time-dependent thermal analysis of U-Mo/Al fuel plates under irradiation to high burnup. The methods and models employed in the code, as well as a preliminary validation of code calculations against RERTR-3 data obtained in PIE, have been previously reported [2]. This paper presents the results of the thermal analyses made using PLATE for the U-Mo/Al experimental fuel plates from the RERTR-1, -2, -3 and -5 irradiation tests. The results of these calculations are now being used in the analysis and correlation of PIE data [3].

2. Overview of the Irradiation Tests

Fourteen different fuel compositions, including twelve metallic alloys, have been irradiated as part of five separate experiments for high-density dispersion fuel development in the Advanced Test Reactor (ATR) at the Idaho National Engineering & Environmental Laboratory [4-7]. The irradiation performance data obtained from these tests has led the US-RERTR program to narrow its focus toward the U-Mo binary alloy system as its primary candidate for use in a high-density dispersion fuel. The RERTR-1 and -2 experiments were identical in design and the experimental fuel test matrices differed only for a few fuel plates; the principal difference in the two experiments was in test duration, with RERTR-1 being discharged at low burnup and RERTR-2 continuing irradiation to much higher burnup. In the same way, RERTR-4 and -5 were similar experiments irradiated to different burnup levels.

<u>RERTR-1 & RERTR-2</u>

These irradiation experiments were the first attempts by the US-RERTR program to irradiate high-density metallic alloy fuels dispersed in an aluminum matrix. These experiments were scoping in nature having the intent of investigating the feasibility of the various fuel system candidates under consideration, so the experimental fuel plates were fabricated with fuel particle loadings of only 25 to 30 vol.-% in the meat, giving meat-averaged uranium densities of ~4 g/cm^3. The particular focus of these experiments was to observe the phenomena of fuel-matrix interaction and fuel particle swelling under irradiation. Fuel plate powers, and consequently temperatures, were maintained low.

Sixty-four miniature fuel plates were fabricated using a variety of uranium alloys based on the U-Nb-Zr and U-Mo binary and ternary systems and irradiated to nominal U-235 burnup levels of 40 and 70%. PIE of these fuel plates revealed poor performance of the U-Nb-Zr fuel alloys; fuel plates fabricated with these alloys exhibited large fuel plate thickness increases caused by both extensive fuel-matrix reaction and incipient breakaway swelling of the fuel particles themselves. Fuel plates fabricated with the U-4Mo alloy showed similar poor behavior. The U-Mo alloys fabricated with at least 6 wt.% Mo, however, performed well up to 70% burnup. The U-Mo alloys with ternary additions (Ru, Pt, Os), known to enhance the stability of the cubic γ-U phase out-of-pile, showed no significant improvement over the binary alloys under irradiation.

<u>RERTR-3</u>

The RERTR-3 experiment was designed to test experimental fuel plates under irradiation conditions considered aggressive for research reactor fuels. Forty-seven miniature fuel plates were fabricated and irradiated to a nominal U-235 burnup level of 40%. Based on the results of the RERTR-1 and -2 experiments, the RERTR-3 experiment focused principally on the U-Mo binary alloy fuels with $6 \leq Mo \leq 10$ wt.%. In this experiment the test fuels were fabricated with fuel particle loadings of over 50 vol.-% in the meat, giving meat-averaged uranium densities of up to 8.5 g/cm^3.

PIE of these fuel plates showed generally acceptable fuel performance. Fuel swelling was relatively low, with no tendency toward breakaway behavior apparent from microscopy.

However, at the elevated fuel temperatures of this experiment significant fuel-matrix interaction was observed. In fact, fuel-matrix interaction was so extensive that no matrix Al remained in the hot central portion of the fuel meat in some fuel plates. Nonetheless, acceptable fuel plate performance was achieved even in cases where all of the matrix Al phase was consumed.

RERTR-4 & RERTR-5

The RERTR-4 and -5 experiments were designed to test larger fuel plates under prototypic research reactor conditions. Each experiment contained thirty-two fuel plates irradiated to nominal U-235 burnup levels of 50 and 80%. These experiments continued to focus on the U-Mo binary alloy fuels with $6 \leq Mo \leq 10$ wt.%. However, the high-burnup RERTR-4 experiment included two fuel plates of an innovative U-10Mo monolithic fuel design. The monolithic fuel design is not a dispersion fuel, but rather an aluminum alloy-clad U-10Mo foil. This fuel design is very attractive since meat-averaged uranium densities much higher than 8 g/cm^3 are possible, and fuel-matrix interaction is mitigated by the small aluminum-to-fuel contact area of the foil. The irradiation of these experiments was completed recently, and PIE is still in progress; preliminary results will be given at this conference [3].

Some uncertainty in the irradiation conditions for these two experiments exists due to their uncertain configuration in the ATR during their first three cycles of irradiation. For this reason PIE data for fuel plates from these tests have not been used in the validation of code calculations or refinement of performance models that are sensitive to irradiation parameters. Furthermore, as-run plate power calculations for the high-burnup RERTR-4 test are not yet available for later cycles, so PLATE calculations are not presented for fuels from this experiment.

3. PLATE Calculations for RERTR-1, -2, -3 and -5

The PLATE code was used to perform calculations for all the binary U-Mo/Al ($6 \leq Mo \leq 10$ wt.%) experimental fuel plates fabricated by a variety of methods (e.g., atomized and machined fuel powders) and irradiated as part of the RERTR-1, -2, -3 and -5 tests using plate-specific fabrication data and cycle-by-cycle as-run plate powers calculated by the ATR physics analysis staff. Comparison of calculated results with experimental data obtained in PIE has been performed most extensively for the fuel plates from RERTR-3 [2]. Much less comparison has been possible for fuel plates from the other RERTR experiments, and calculated results for these fuel plates should be considered preliminary at this time; in particular, the ambiguity regarding irradiation conditions for RERTR-5 introduces considerable uncertainty in the calculated values for fuel plates from this test. Final fuel plate powers are not yet available for RERTR-4, so no calculations for this test have been attempted at this time.

Figures 1 through 4 provide an overview of the calculated results. Figure 1 shows the wide range of fuel plate heat fluxes and burnups achieved in the RERTR series of U-Mo/Al fuel tests; fuel plates have been irradiated having heat fluxes from 50 to 400 W/cm^2 up to a U-235 burnup of 70%. Results from RERTR-4 will provide additional data at moderate-to-high heat fluxes similar to (but somewhat lower than) RERTR-5 for fuel plates irradiated to 80% burnup.

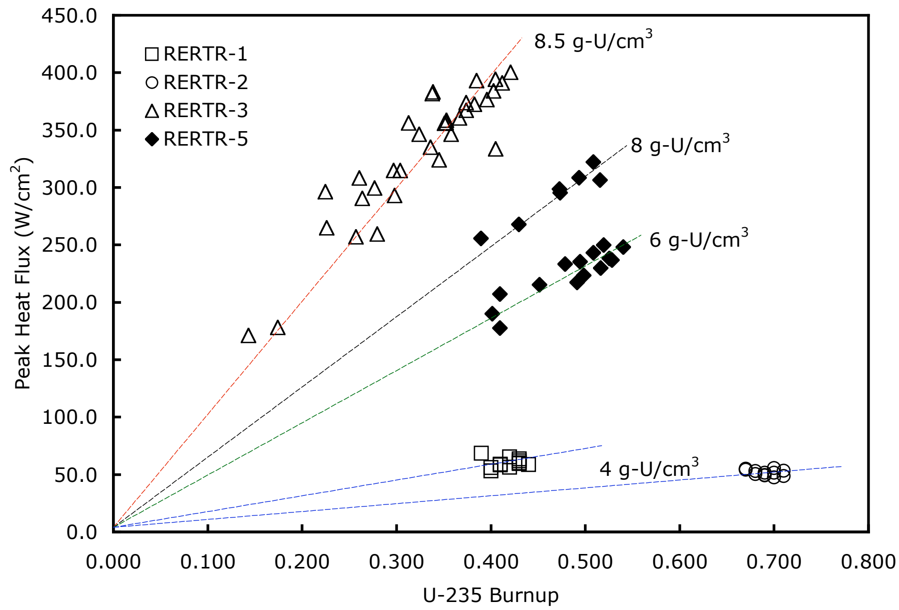

Figure 1. Heat fluxes and burnups for RERTR experimental fuel plates.

Figure 2 shows the calculated peak fuel temperatures for the experimental fuel plates. In no case does the peak fuel temperature occur at beginning-of-life. Due to ATR power levels that change from cycle-to-cycle, but especially due to the accumulation of the low-conductivity reaction product phase (and associated depletion of the high-conductivity Al matrix phase) which significantly degrades the effective fuel meat thermal conductivity during irradiation, the peak fuel temperatures in these fuel plates occur some time after initial startup. In the cases of the

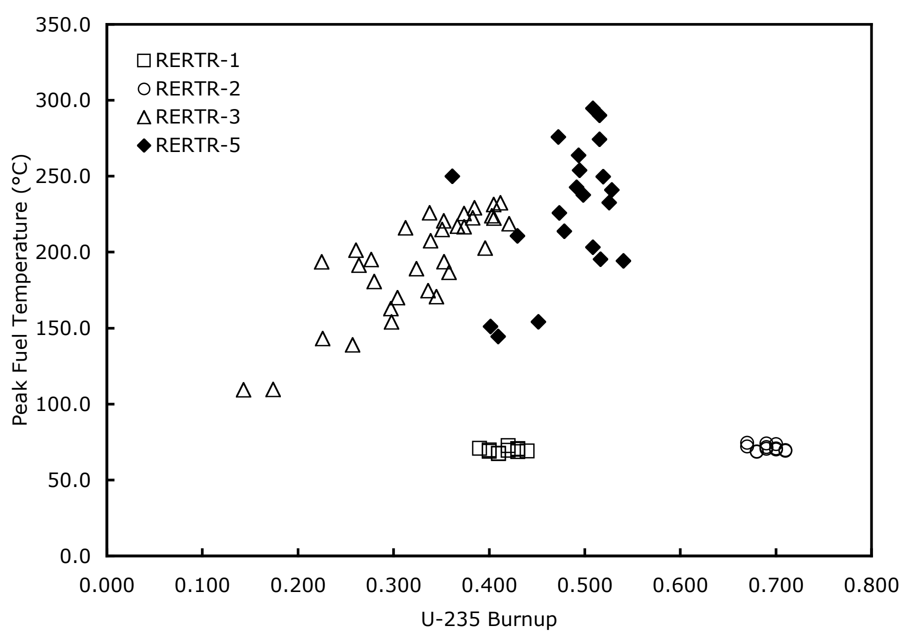

Figure 2. Peak fuel temperatures for RERTR experimental fuel plates.

high power fuel plates from RERTR-3 and -5, peak fuel temperatures can be as much as 80°C higher than beginning-of-life fuel temperatures; the recognition of this is precisely what motivated the development of the PLATE thermal analysis code. Within the data sets for the RERTR-3 and -5 fuel plates, the fuel plates with similar burnups operated as similar powers. The variation in peak fuel temperatures for fuel plates with similar power levels is explained primarily by fabrication differences (e.g., at a constant fuel loading, spherical fuel particles produce less reaction product than non-spherical fuel particles). This is evident from Figure 3, where large differences in the volume of reaction product generated from fuel-matrix interaction can be seen for fuel plates having similar peak fuel temperatures.

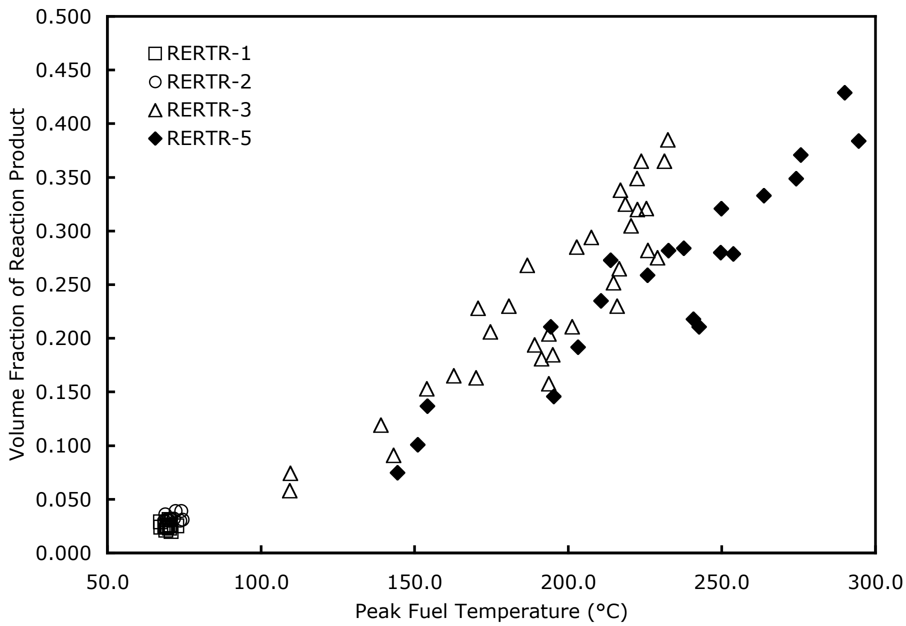

Figure 3. Fuel-matrix interaction as a function of fuel temperature for RERTR experimental fuel plates.

Finally, Figure 4 shows the calculated values for fuel plate thickness increase as a function of fuel fission density. Plate thickness increases are the composite result of multiple sources of dimensional change: fuel-matrix interaction which consumes a high-density fuel alloy and produces a low-density reaction product, decreases in the fuel meat fabrication porosity, and fuel swelling. At high burnup, fuel swelling is the dominant component; at low burnup and high temperature, fuel-matrix interaction dominates. As currently modeled in PLATE, U-Mo fuel swelling is an athermal phenomenon. For the U-Mo fuel plates fabricated using spherical fuel powder as part of the RERTR-3 test, PLATE calculations of plate thickness increase have been shown to agree with measured values to ±10% [8]; agreement with plates fabricated using non-spherical fuel powder is not this good due to the difficulty in accurately characterizing the fuel powder size and shape distributions which have a substantial effect on the volume of reaction product that is generated.

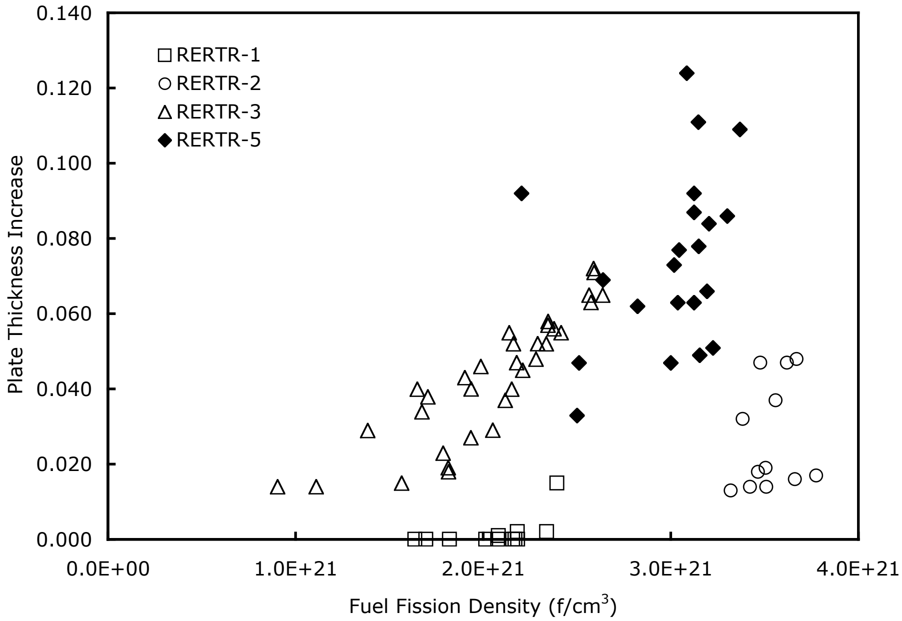

Figure 4. Fuel plate thickness increases as a function of end-of-life fuel particle fission densities for RERTR experimental fuel plates.

4. Parametric Studies for U-Mo Dispersion Fuels

The use of the PLATE code to perform parametric studies for U-Mo/Al dispersion fuel plates has highlighted a number of important issues. First, fuel-matrix interaction and its influence on fuel temperatures is a dominating effect as plate powers increase. For an atomized U-Mo/Al fuel plate of the RERTR-3 design fabricated at 8 g-U/cm^3 and operated at a constant heat flux of 350 W/cm^2, fuel-matrix interaction produces a reaction product that makes up approximately 34% of the fuel meat volume by 40% burnup. The end-of-life fuel meat thermal conductivity in this case is approximately 0.13 W/cm-°C, more than a factor of five decrease compared to the as-fabricated fuel meat thermal conductivity of 0.74 W/cm-°C (see Figure 5), resulting in a peak fuel temperature at end-of-life that is 60°C higher than at beginning-of-life.

Second, the corrosion of aluminum cladding produces a predominantly boehmite reaction product of very low thermal conductivity on the surface of fuel plates. While the rate of growth of this corrosion product varies widely from reactor to reactor, its impact on fuel temperatures can be substantial for large corrosion rates/thick corrosion layers. Figure 6 shows the calculated peak fuel temperature as a function of corrosion product thickness; for the purposes of this illustration, the calculation assumed a linear growth rate of a uniformly thick corrosion product on the surface of a fuel plate of the RERTR-3 design operated at a constant heat flux of 275 W/cm^2 to 40% burnup.

Lastly, PLATE calculations have revealed the importance of characterizing the fuel particle shape and size distribution, as these fabrication variables have a significant influence on fuel plate performance calculations. Figure 7 shows the results of a series of calculations on the

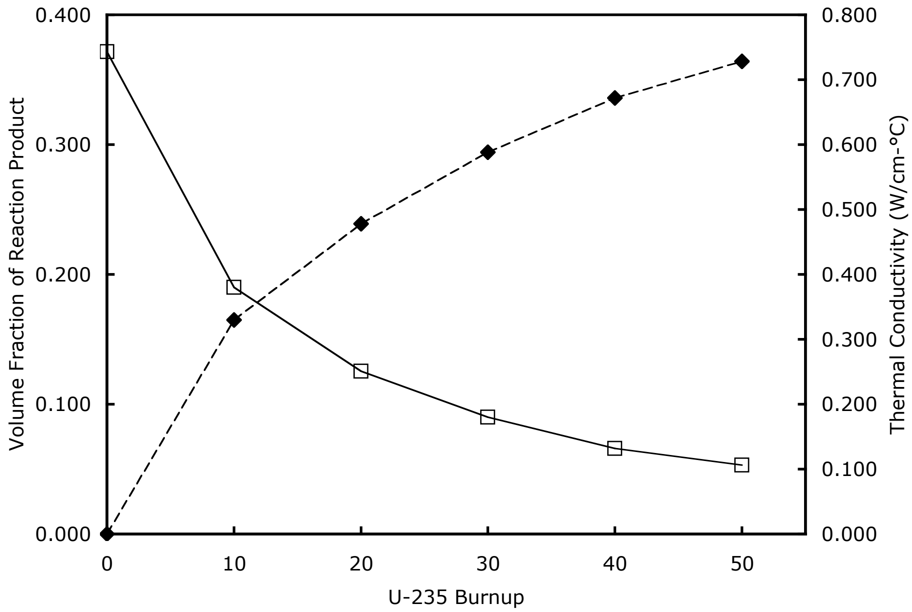

Figure 5. Degradation of fuel meat thermal conductivity (□) with accumulation of the fuel-matrix reaction product phase (◆).

example fuel plate of the RERTR-3 design operated at a constant heat flux of 275 W/cm^2 to 40% burnup, with the final volume fraction of reaction product and the peak fuel temperature plotted as a function of fuel particle diameter for spherical fuel particles. As can be seen in the figure, the volume of reaction product produced increases by a factor of three as the fuel particle diameter is reduced from 80 to 20 µm. This effect is due to the fact that fuel-matrix interaction is a function of the surface area available for reaction, and the specific surface area of a spherical fuel particle increases as the diameter decreases. The effect can be even more dramatic for fuel particles fabricated by machining/grinding techniques since the specific surface area of non-spherical particles can be substantially higher than for spherical particles of the same mass or characteristic dimension.

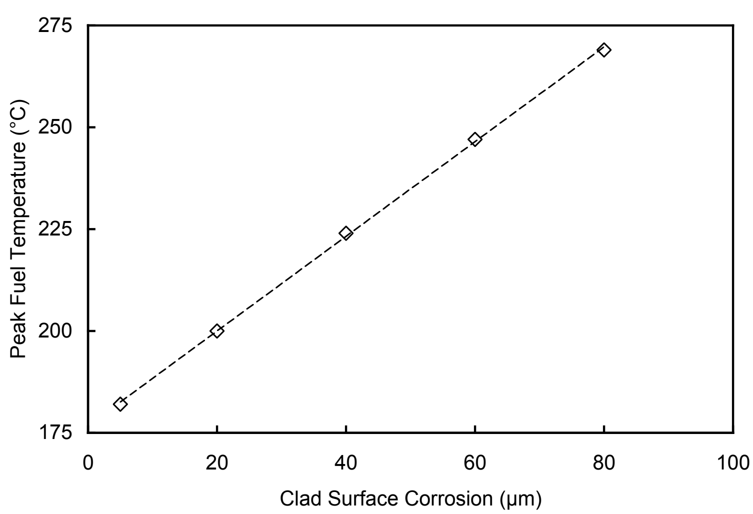

Figure 6. Sensitivity of peak fuel temperature to cladding corrosion.

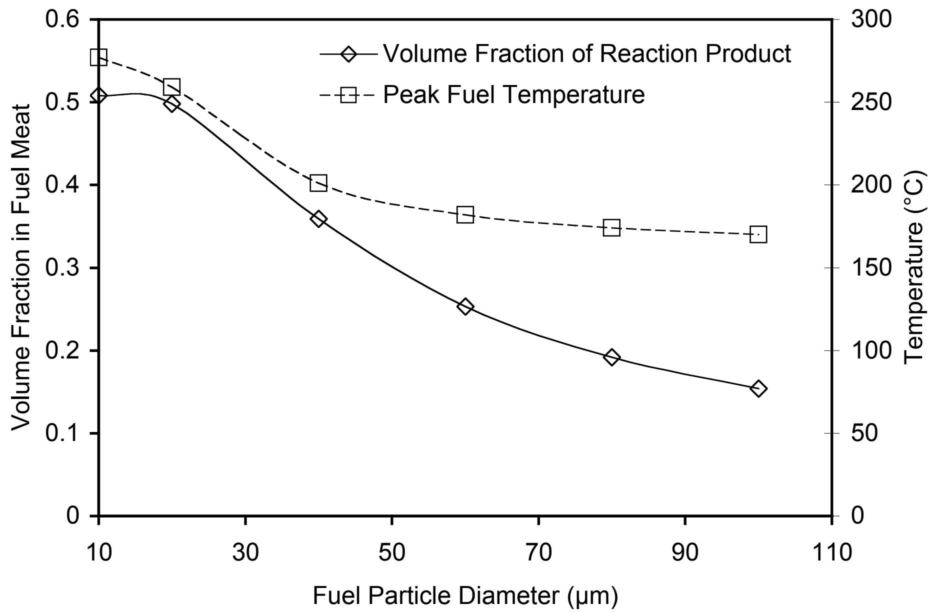

Figure 7. Sensitivity of fuel-matrix interaction and fuel temperature to fuel particle size (for spherical particles).

5. Summary and Conclusions

The fuel performance code PLATE developed to analyze the thermal performance of high-density U-Mo/Al dispersion fuel plates during irradiation has been used to perform a preliminary evaluation of all the U-Mo/Al experimental fuel plates from the RERTR-1, -2, -3 and -5 tests. These evaluations indicate that these test fuels have operated with heat fluxes that range from 50 to 400 W/cm^2. Under these conditions, fuel-matrix interaction is calculated to have generated a reaction product that makes up as much as 40% of the fuel meat volume, with resulting peak fuel temperatures as high as 290°C.

Parametric analyses made using PLATE have led to a much better understanding of the fabrication and irradiation variables important to U-Mo/Al irradiation performance. First, the total fuel surface area should be minimized in order to minimize fuel-matrix interaction. In this regard spherically-shaped fuel particles have an advantage over non-spherical shapes; for any shape, however, the use of large quantities of small fuel particles (fines) should be avoided. Calculations have also shown that knowledge of the fuel particle size and shape distribution will be necessary in order to make good predictions of fuel plate performance. Second, fuel-matrix interaction is a sensitive function of temperature; thus, efforts should be taken to keep temperatures as low as possible for U-Mo/Al fuels. For this reason cladding surface corrosion must be kept low for this fuel form.

6. References

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